Neutrino-Induced Fission and r-Process Nucleosynthesis

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ABSTRACT

An r-process scenario with fission but no fission cycling is considered to account for the observed abundance patterns of neutron-capture elements in ultra-metal-poor stars. It is proposed that neutrino reactions play a crucial role in inducing the fission of the progenitor nuclei after the r-process freezes out in Type II Supernovae. To facilitate neutrino-induced fission, the proposed r-process scenario is restricted to occur in a low-density environment such as the neutrino-driven wind from the neutron star. Further studies to develop this scenario are emphasized.

Subject headings: nuclear reactions, nucleosynthesis, abundances — stars: Population II — supernovae: general

1. Introduction

The nuclei above ^{56}Fe are produced dominantly by the slow (s) and rapid (r) neutron-capture (n-capture) processes. The main s-process occurs in low-mass asymptotic giant branch stars and mainly produces the nuclei above ^{88}Sr while the weak s-process occurs in massive stars and mainly produces the nuclei up to ^{88}Sr (e.g., Käppeler, Beer, & Wisshak 1989). It is considered here that Type II supernovae (SNe II) resulting from evolution of massive stars are the major sources for the r-process (e.g., Qian 2000). As massive stars have much shorter lifetimes than low-mass stars, SNe II made the dominant contributions to the abundances of n-capture elements in metal-poor (MP) stars that were formed in the early Galaxy. Detailed abundance patterns covering many n-capture elements have been obtained for a number of ultra-metal-poor (UMP) stars with [Fe/H] ≈ -3 (e.g., Sneden et al. 2000; Westin et al. 2000; Hill et al. 2001). This Letter discusses the implications of these abundance patterns for r-process nucleosynthesis in SNe II.

Starting with a large abundance ratio of neutrons relative to the seed nuclei (i.e., a large neutron-to-seed ratio), the r-process produces a distribution of neutron-rich progenitor

nuclei far from stability through the interplay of rapid neutron capture, photo-disintegration, and β-decay. Depending on the neutron-to-seed ratio, the r-process may produce progenitor nuclei that subsequently undergo fission on a short timescale. This limits the range of nuclei involved in the r-process and may result in a cyclic flow between the terminating nuclei and their fission products (i.e., fission cycling). The role of fission in r-process nucleosynthesis was discussed by the very first papers that proposed the r-process (Burbidge et al. 1957; Cameron 1957). Fission cycling was discussed in detail by Seeger Fowler, & Clayton (1965) and was included in many r-process studies (e.g., Rauscher et al. 1994; Freiburghaus, Rosswog, & Thielemann 1999; Cameron 2001). Fission was also invoked to explain certain features of the observed r-process abundance patterns (r-patterns). For example, Cameron (1957) attributed the small peak in the rare earth region (with mass numbers $A \sim 160$) of the solar r-pattern to fission of the progenitor nuclei with $A \sim 287$.

An r-process scenario with fission but no fission cycling is considered here to account for the observed abundance patterns in UMP stars (§2). It is proposed that fission may be induced by neutrino reactions with the progenitor nuclei after the r-process freezes out (i.e., exhausts all the initial neutrons) in SNe II. The conditions under which this scenario could be realized and some possible features of the resulting r-pattern are discussed (§3). Further studies to develop this scenario are emphasized (§4).

2. Abundance Patterns in UMP Stars

Extensive observations showed that the abundances of the heavy n-capture elements from Ba up to Pt in UMP stars exhibit remarkable regularity and follow the solar r-pattern rather closely (e.g., Sneden et al. 2000; Westin et al. 2000). However, as shown in Figure 1a, the observed abundances of the light n-capture elements Rh, Pd, Ag, and Cd in the UMP star CS 22892-052 (Sneden et al. 2000) are too low relative to the solar r-pattern (Arlandini et al. 1999) that is translated to fit the region above Ba ($A > 130$). A possible explanation for this is that different production mechanisms may be responsible for the n-capture elements below and above Ba in UMP stars. For example, fission cycling tends to produce a rather robust r-pattern at $A \gtrsim 130$ (e.g., Freiburghaus et al. 1999). So the regular abundance pattern for Ba and above in UMP stars could be attributed to an r-process with a neutron-to-seed ratio that is sufficiently high for fission cycling to occur. Then the light n-capture elements in UMP stars could be attributed to some other r-process with a neutron-to-seed ratio that is appropriate for producing these elements only or to the weak s-process that might operate at some unusually high efficiency in the earliest generations of massive stars.

However, the attribution of the abundances of Ba and above in UMP stars to an r-

process with fission cycling may be in conflict with the data on another UMP star CS 31082-001. As can be seen from Figure 1b, the observed abundances in CS 31082-001 (Cayrel et al. 2001; Hill et al. 2001) and CS 22892-052 (Sneden et al. 2001) follow approximately the same pattern except that the differences in the abundances of Os and the radioactive elements Th and U between the two stars appear to be significantly larger than those for the other elements (the differences in the abundances of Ir and Pb may also be significant but the uncertainties are large). As can be best seen by considering the abundance ratio Th/Eu, the data on CS 31082-001 and CS 22892-052 do not support a robust r-pattern at $A \gtrsim 130$ that is expected from fission cycling. In view of the extremely low [Fe/H] values of ≈ -3 for the two stars, it is reasonable to assume that both stars were formed during the first few Gyr after the onset of Galactic r-process nucleosynthesis. So both stars should have ages of ~ 10 Gyr. Under the assumption of a fixed r-process yield ratio of Th relative to Eu, the difference Δt in the ages of the two stars is

$$\Delta t = \frac{\tau_{232}}{\log e}\left|\log\left(\frac{\rm Th}{\rm Eu}\right)_{\rm CS\ 31082} - \log\left(\frac{\rm Th}{\rm Eu}\right)_{\rm CS\ 22892}\right|,$$

where $\tau_{232} = 20.3$ Gyr is the lifetime of ^{232}Th. The data $\log\epsilon({\rm Eu}) = -0.70\pm0.09$, $\log\epsilon({\rm Th}) = -0.96 \pm 0.03$ for CS 31082-001 (Cayrel et al. 2001; Hill et al. 2001) and $\log\epsilon({\rm Eu}) = -0.93 \pm 0.09$, $\log\epsilon({\rm Th}) = -1.60 \pm 0.07$ for CS 22892-052 (Sneden et al. 2001), where $\log\epsilon({\rm E}) = \log({\rm E/H}) + 12$, give $\Delta t = 19.2 \pm 7.0$ Gyr. This is totally unreasonable. Thus, the assumption of a fixed r-process yield ratio of Th relative to Eu must be invalid and the r-pattern at $A \gtrsim 130$ is not robust.

While it may be possible to accommodate the data on both CS 22892-052 and CS 31082-001 by having variable amounts of fission cycling in the r-process, an alternative scenario with fission but no fission cycling is considered here to explain the observed abundance patterns of n-capture elements in these two and possibly other UMP stars. It is proposed that an r-process produces a freeze-out distribution of progenitor nuclei covering $190 \lesssim A < 320$ with a peak at $A \sim 195$ (corresponding to the magic neutron number $N = 126$). The required neutron-to-seed ratio is high, but it is assumed that no fission cycling occurs during the r-process. This may be consistent with some recent studies of fission barriers for extremely neutron-rich nuclei (Mamdouh et al. 2001). As the progenitor nuclei β-decay towards stability after freeze-out, all of those with $260 \lesssim A < 320$ eventually undergo spontaneous fission (e.g., Cameron 2001). Due to the strong influence of the closed proton and neutron shells at ^{132}Sn, the fission of $260 \lesssim A < 320$ is expected to produce one fragment at $A \sim 132$ and the other at $130 \lesssim A < 190$ although the detailed fission yields may be more complicated (e.g., Hulet et al. 1989). Some of the progenitor nuclei with $230 \lesssim A < 260$ would also undergo spontaneous fission during decay towards stability, thereby producing one fragment again at $A \sim 132$ and the other at $100 \lesssim A < 130$. The possibility of fission for

$230 \lesssim A < 260$ may be greatly enhanced by reactions with the neutrinos emitted in SNe II as these nuclei could be highly excited by such reactions. Neutrino reactions may even induce fission of the progenitor nuclei with $190 \lesssim A < 230$. Experiments using energetic particles to induce fission of the stable or long-lived nuclei in this mass range showed that the fission mode is dominantly symmetric with no preference for a fission fragment at $A \sim 132$ and the mass ratio of the two fission fragments is $\sim$ 1–1.2 (e.g., Britt et al. 1963; see Möller et al. 2001 for recent theoretical interpretation). So the neutrino-induced fission of $190 \lesssim A < 230$ is expected to produce fragments at $86 \lesssim A < 125$.

Thus, in the r-process scenario proposed here, the fission of the progenitor nuclei with $190 \lesssim A < 320$ during decay towards stability after freeze-out would produce nuclei with $86 \lesssim A < 190$ (see Table 1). In view of the mass range of the progenitor nuclei and their fission products, it is tempting to consider the proposed r-process scenario as the dominant source for all the n-capture elements observed in UMP stars. The ratio of the fission yields at $86 \lesssim A < 190$ relative to the surviving abundances at $190 \lesssim A < 260$ depends on the number of neutrino reactions experienced by each progenitor nucleus after freeze-out. Variation of this number among individual SNe II may explain why the observed abundances of Os and above ($A \gtrsim 190$) relative to those of the n-capture elements below Os are significantly different in CS 22892-052 and CS 31082-001. The conditions under which the proposed scenario could be realized are discussed below.

3. Neutrino-Induced Fission and r-Process Nucleosynthesis

In the r-process scenario proposed here, all the initial neutrons are exhausted when the heaviest progenitor nuclei with $A \sim 320$ are produced. Except for the progenitor nuclei perhaps with $300 \lesssim A < 320$ that are mostly produced when the r-process is running out of neutrons, the freeze-out abundances of the other progenitor nuclei are expected to be inversely proportional to their β-decay rates. The β-decay rates for the progenitor nuclei with $190 \lesssim A < 200$ ($N = 126$) are ~ 10 times smaller than those for $200 \lesssim A < 300$ (Möller et al. 1997). With this crude guidance to the freeze-out abundances (see Table 1), the ratio of the fission yields at $86 \lesssim A < 190$ relative to the surviving abundances at $190 \lesssim A < 260$ is $\sim (2f + 0.5) : (1 - f)$ if a fraction f of the progenitor nuclei with $190 \lesssim A < 260$ and all of those with $260 \lesssim A < 320$ undergo fission during decay towards stability after freeze-out. By assigning the n-capture elements below Os to the fission products and considering Pb as the dominant decay product of the surviving nuclei with $210 \lesssim A < 260$, it can be estimated from Figure 1 that $f \sim 40\%$ is required to account for the gross features of the observed abundance pattern in CS 22892-052 and $f \sim 20\%$ for CS 31082-001.

Without excitation by energetic particles, the probability of fission increases with Z^2/A, where Z is the atomic number of the nucleus. All of the progenitor nuclei with $260 \lesssim A < 320$ are expected to undergo spontaneous fission eventually as Z increases during their decay towards stability (e.g., Cameron 2001). In contrast, as the stable or long-lived nuclei with $190 \lesssim A < 230$ do not undergo any significant spontaneous fission, neither would their neutron-rich progenitors in the absence of high excitation. The probability of spontaneous fission during decay towards stability may not be significant even for the progenitor nuclei with $230 \lesssim A < 260$ (e.g., Meyer et al. 1989). However, the progenitor nuclei and their daughters can be highly excited by reactions with the neutrinos emitted in SNe II. The typical excitation energy is ~ 30 MeV for ν_e capture and ~ 15 MeV for reactions with ν_μ, $\bar{\nu}_\mu$, ν_τ, and $\bar{\nu}_\tau$ (e.g., Qian et al. 1997). Thus, neutrino reactions may be crucial in inducing the fission of $\sim$ 20–40% of the progenitor nuclei with $190 \lesssim A < 260$ during decay towards stability after freeze-out. Note that neutrino-induced fission should be unimportant during the r-process as the rates for ν_e capture must be severely limited in order to produce the abundance peak at $A \sim 195$ (Fuller & Meyer 1995). An essential question is then whether there would be a sufficient number of neutrino reactions with the progenitor nuclei after the r-process freezes out in SNe II.

The gravitational binding energy of the neutron star formed in SNe II is radiated in neutrinos over a period of ~ 20 s (e.g., Woosley et al. 1994). This is the upper limit on the duration of the r-process so that the progenitor nuclei can have a significant number of neutrino reactions after freeze-out. The duration of the r-process is dominantly controlled by the β-decay lifetimes of the progenitor nuclei. For an r-process path in a low-density environment where electrons are nondegenerate, the typical β-decay lifetimes are ~ 0.1 s for ~ 10 progenitor nuclei with closed neutron shells and ~ 0.01 s for those without (Möller et al. 1997). It would then take < 4 s to reach the progenitor nuclei with $A \sim 320$. So all the progenitor nuclei could have a significant number of neutrino reactions after freeze-out if the r-process scenario proposed here is restricted to occur in a low-density environment such as the neutrino-driven wind from the neutron star (e.g., Woosley et al. 1994) instead of a high-density environment such as an accretion disk (Cameron 2001).

Another concern is the probability of fission following a neutrino reaction. A neutron-rich nucleus far from stability can de-excite by emitting neutrons instead of undergoing fission. Increase in Z would help neutrino-induced fission compete with neutron emission. Based on the β-decay lifetimes estimated by Möller et al. (1997), Z could increase by ~ 8 units within ~ 10 s for the progenitor nuclei with $190 \lesssim A < 260$. Thus, the crucial role of neutrino-induced fission in the r-process scenario proposed here relies on the assumption that the probability of fission following a neutrino reaction is or becomes significant during the first ~ 8 steps in the β-decay chains of the progenitor nuclei with $190 \lesssim A < 260$. This assumption

should be checked by detailed calculations in the future. If a typical probability of fission is $P_f \sim 50\%$ (i.e., comparable to that of neutron emission), a fraction $f \sim P_f[1 - \exp(-n)] \sim$ 20–40% of the progenitor nuclei would undergo fission after a total number $n \sim 0.5$–1.6 of neutrino reactions per nucleus. The values of P_f to give $f \sim$ 20–40% may be reduced somewhat by increasing n to ~ 3. A similar level of neutrino reactions would completely account for the production of $A = 183$–187 by neutrino-induced neutron emission from the progenitor nuclei in the peak at $A \sim 195$ after freeze-out (Qian et al. 1997; Haxton et al. 1997).

Given that the proposed r-process scenario with fission could be realized, it is interesting to note some features of the corresponding yield pattern that are not so evident from the data for CS 22892-052 and CS 31082-001. As proposed, the freeze-out distribution of progenitor nuclei covers $190 \lesssim A < 320$ with a peak at $A \sim 195$. The fission of $\sim$ 20–40% of the progenitor nuclei with $190 \lesssim A < 260$ and all of those with $260 \lesssim A < 320$ would produce enhanced fission yields at $A \sim 90$ and $A \sim 132$. The enhancement at $A \sim 90$ is expected from fission of the progenitor nuclei in the peak at $A \sim 195$, while that at $A \sim 132$ from the common fission fragment at this position for all the progenitor nuclei with $230 \lesssim A < 320$. Thus, the typical yield pattern from the proposed r-process scenario has a peak at $A \sim 195$ and enhanced yields at $A \sim 90$ and $A \sim 132$. This yield pattern could be modified by capturing the neutrons released from fission. For example, the positions of the peak and the enhanced fission yields could be shifted to somewhat higher A. Such shifts in the yield pattern due to residual neutron capture were found in r-process scenarios with fission cycling (Rauscher et al. 1994; Freiburghaus et al. 1999). In any case, the r-process scenario proposed here could not account for the peak at $A = 130$ in the solar r-pattern and therefore could provide one of the diverse sources for the r-process that are required by the model of Wasserburg, Busso, & Gallino (1996) to explain the meteoritic data on ^{129}I and ^{182}Hf. The yield pattern resulting from this scenario might also be similar to the r-pattern that was derived by Qian & Wasserburg (2001) for the high-frequency kind of SNe II based on the model of Wasserburg et al. (1996) and observations of MP stars.

There may be a hint for the shift of the enhanced fission yields at $A \sim 132$ to higher A from studies of the Ba isotopic composition in the UMP star HD 140283. The three r-process isotopes of Ba are ^{135}Ba, ^{137}Ba, and ^{138}Ba. The odd-A isotopes of an element have finite nuclear magnetic moments that lead to hyperfine structure of the atomic spectra. Magain (1995) performed a detailed analysis of the Ba spectra for HD 140283 and concluded that the fraction of the odd-A Ba isotopes is 0.08 ± 0.06, corresponding to abundance ratios ^{138}Ba/^{135}Ba and ^{138}Ba/^{137}Ba of > 6. By capturing the neutrons released from fission, the enhanced fission yields at $A \sim 132$ could be shifted to produce this steep rise of the yield at $A = 138$. It is also possible that the Ba in HD 140283 may not be of pure r-process

origin. In any case, the Ba isotopic composition in UMP stars has important implications for n-capture processes in the early Galaxy and deserves further observational studies.

4. Discussion and Conclusions

Clearly, much further work is required to develop the r-process scenario with fission as proposed here. On the observational side, extensive studies of the abundance patterns of n-capture elements should be carried out for many more UMP stars to identify regularities and variations. The paucity of data on the light n-capture elements below Ba should be remedied. As Pb is the dominant decay product of the progenitor nuclei with $210 \lesssim A < 260$, accurate determination of its abundance should be made. Detailed analyses of Ba isotopes are also valuable as discussed in §3. On the theoretical side, the foremost issue to investigate is the probability of neutrino-induced fission for extremely neutron-rich nuclei and the corresponding fission yields. Numerical calculations with an extensive network including neutrino reactions are needed to make a detailed comparison between the theoretical yields and the observed abundance patterns. The effects of the energy release from fission on the thermodynamic and hydrodynamic evolution of the r-process environment are also interesting to study. Last but certainly not the least, attempts should be made to understand how the conditions for the proposed r-process scenario are realized in a low-density environment such as the neutrino-driven wind in SNe II.

A crucial quantity characterizing the r-process conditions is the neutron-to-seed ratio R. By mass conservation, the average mass number $\langle A\rangle$ for the freeze-out distribution of progenitor nuclei is $\langle A\rangle = A_{\rm sd} + R$, where $A_{\rm sd}$ is the mass number of the seed nuclei. With $A_{\rm sd} \sim 90$ obtained in the neutrino-driven wind (e.g., Woolsey et al. 1994), $R \sim 130$ is required to produce $\langle A\rangle \sim 220$ in the proposed r-process scenario (see Table 1). In general, R is determined by the electron fraction Y_e, the entropy S, and the dynamic timescale $\tau_{\rm dyn}$ of the wind. While it remains unclear how the suitable combinations of Y_e, S, and $\tau_{\rm dyn}$ can be obtained in the wind to give $R \sim 130$, several possibilities have been suggested. One is to consider the general relativistic effects of a more massive or compact neutron star. As first shown by Qian & Woosley (1996) and later confirmed by other studies (Cardall & Fuller 1997; Otsuki et al. 2000; Thompson, Burrows, & Meyer 2001), such effects increase S and decrease $\tau_{\rm dyn}$, both favoring higher R. Another possibility is to consider the effects of neutrino flavor mixing. The Y_e in the wind is mostly determined by the competition between $\bar{\nu}_e + p \rightarrow n + e^+$ and $\nu_e + n \rightarrow p + e^-$, and therefore is extremely sensitive to the differences between the luminosities and energy spectra of $\bar{\nu}_e$ and ν_e (Qian et al. 1993). As $\bar{\nu}_\mu$ and $\bar{\nu}_\tau$ have much higher average energy than $\bar{\nu}_e$ and ν_e, mixing between $\bar{\nu}_{\mu(\tau)}$ and $\bar{\nu}_e$ could

significantly reduce Y_e (e.g., Qian & Fuller 1995), again favoring higher R. It is plausible that by including both the effects of general relativity and neutrino flavor mixing, $R \sim 130$ could be obtained in the wind. These issues should be examined by future studies.

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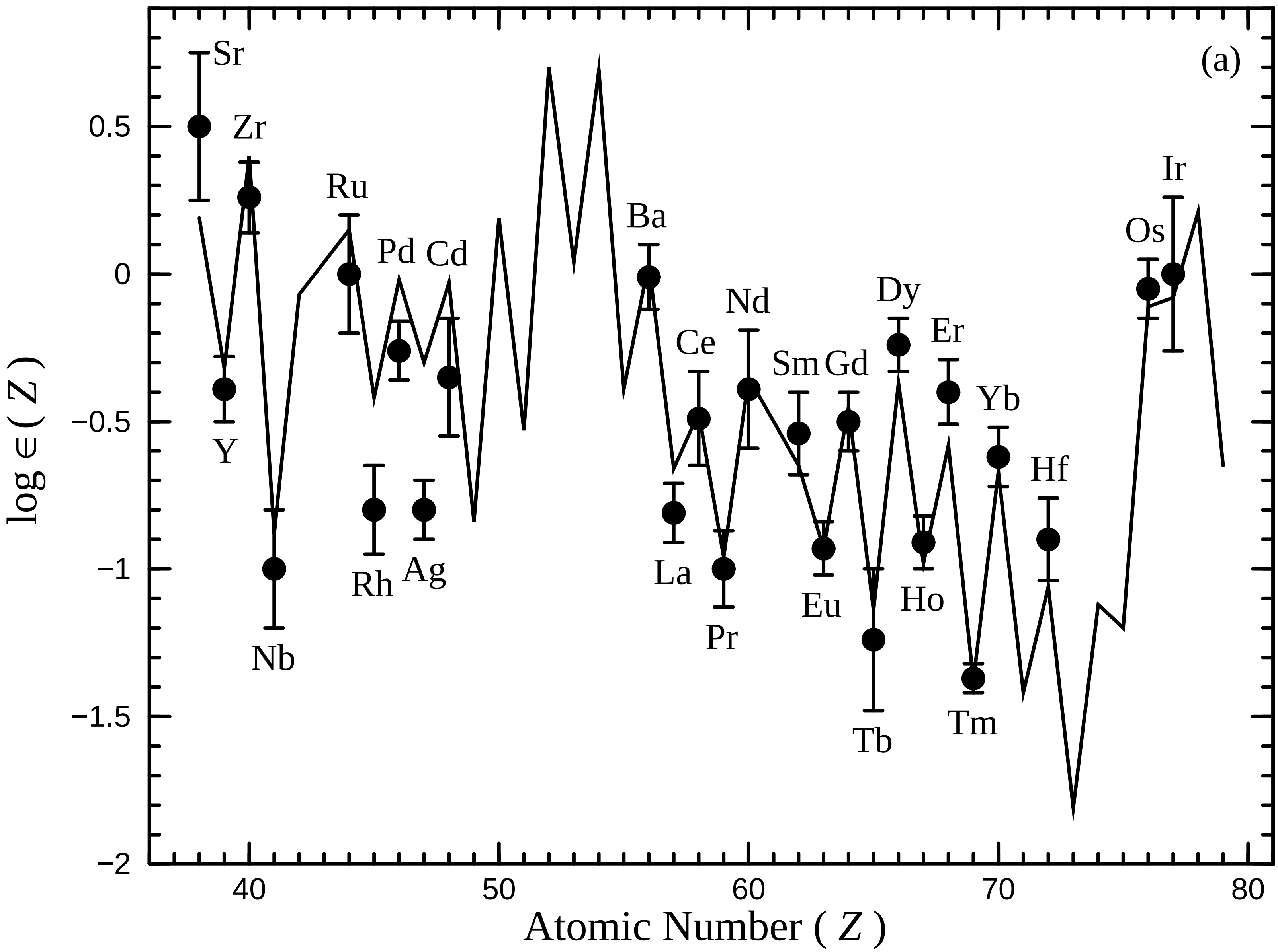
Fig. 1.— (a) Data on n-capture elements in CS 22892-052 (filled circles; Sneden et al. 2000) compared with the solar r-pattern (solid line) that is translated to fit the Eu data. The solar r-pattern is derived by subtracting the stellar-model-based s-process contributions from the solar inventory (Arlandini et al. 1999). (b) Data for CS 31082-001 (open circles with that for Pb slightly shifted for clarity; Cayrel et al. 2001; Hill et al. 2001) compared with those for CS 22892-052 (filled circles). The downward arrows indicate upper limits.

Table 1. Fission During Decay Towards Stability

progenitor nuclei	freeze-out abundances[a]	fission products
$190 \lesssim A < 200$	1	$86 \lesssim A < 109$
$200 \lesssim A < 230$	~ 0.3	$91 \lesssim A < 125$
$230 \lesssim A < 260$	~ 0.3	$A \sim 132$ and $100 \lesssim A < 130$
$260 \lesssim A < 320$	~ 0.4	$A \sim 132$ and $130 \lesssim A < 190$

[a]Normalized so that the total freeze-out abundance of $190 \lesssim A < 200$ (in the peak at $A \sim 195$) is unity.



(a)
Sr
Y
Zr
Nb
Ru
Rh
Pd
Ag
Cd
Ba
La
Ce
Pr
Nd
Sm
Eu
Gd
Tb
Dy
Ho
Er
Tm
Yb
Hf
Os
Ir
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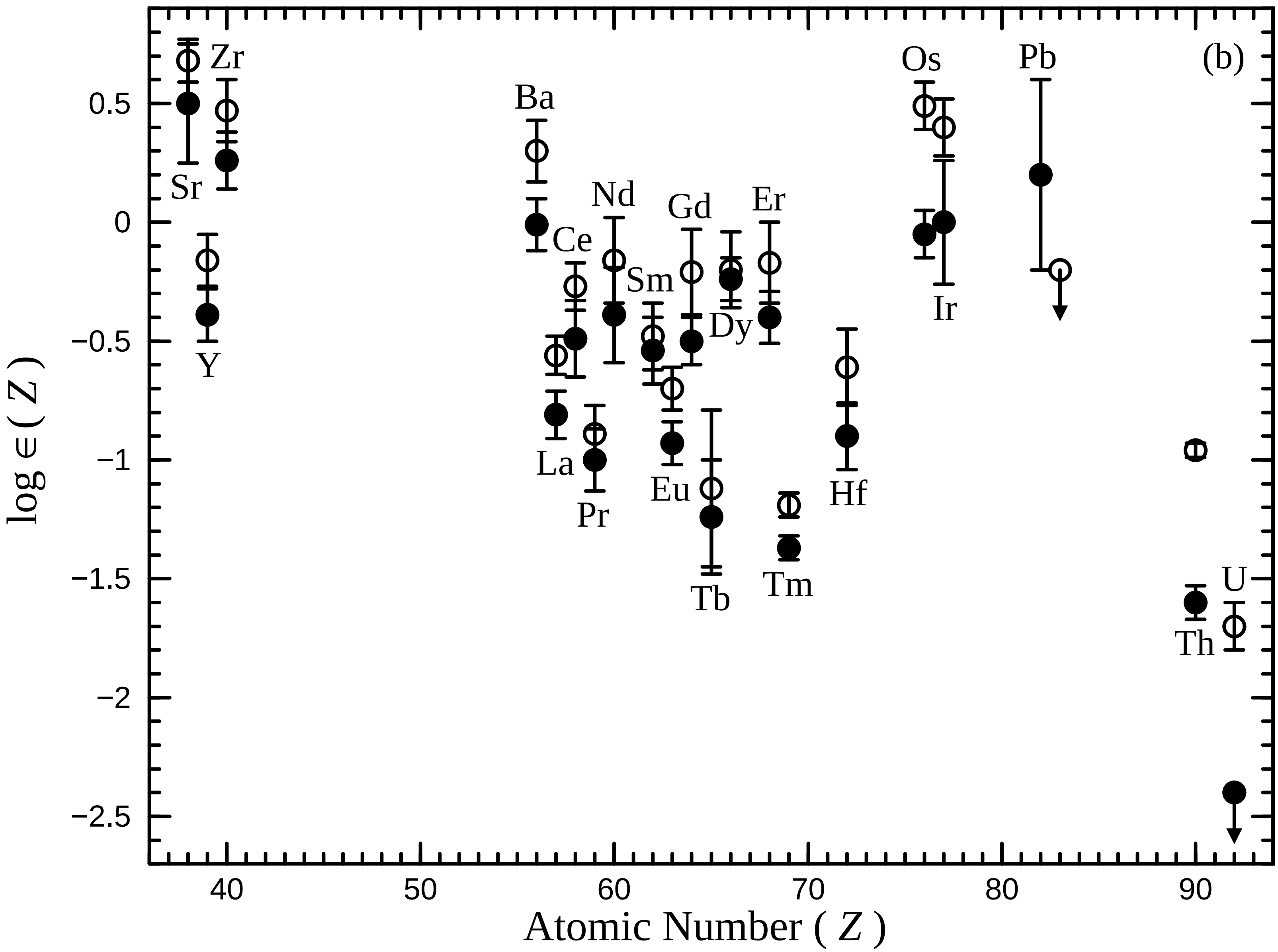
0
−0.5
−1
−1.5
−2
40
50
60
70
80
log ∈ (Z)
Atomic Number (Z)



(b)
Sr
Zr
Y
Ba
La
Ce
Pr
Nd
Sm
Eu
Gd
Tb
Dy
Er
Tm
Hf
Os
Ir
Pb
Th
U
0.5
0
−0.5
−1
−1.5
−2
−2.5
40
50
60
70
80
90
log ∈ (Z)
Atomic Number (Z)